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SIMULATE BEAM NEUTRALIZATION NEAR TARGET FOCUS USING RECONFIGURED PLASMA SOURCES

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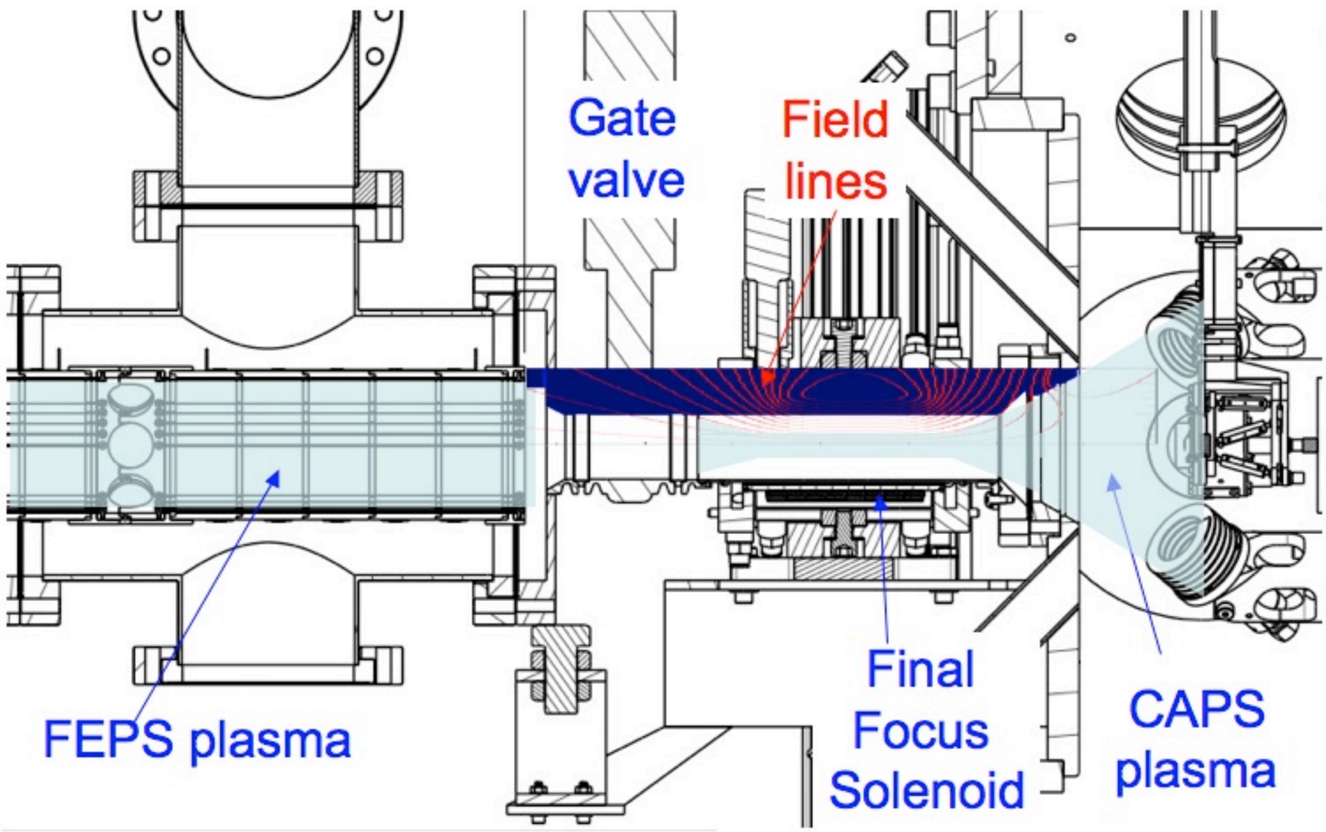

Schematic of existing NDCX configuration showing regions with incomplete plasma fill.

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"Simulate beam neutralization near target focus using reconfigured plasma sources"

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I. INTRODUCTION

This milestone has been accomplished. Particle-in-cell simulations have clarified the effects on the beam that arise from localized regions of incomplete neutralization along the beam path. The beam focal spot size increases and the peak intensity on target decreases when such regions are present. The results clarify the influence of regions where additional plasma sources would improve the beam focusing. The advantage of additional plasma sources has been demonstrated by comparing results obtained with and without plasma in regions where it is presently absent or under-dense. We have found that, in particular, directly introducing plasma into the region immediately upstream of the final-focusing solenoid, and at larger radii within that solenoid, would be beneficial. The implications of this work for the NDCX experiments are discussed.

Our main purpose in this report is to clarify the effects on the beam of inadequate plasma density in distinct spatial regions, and to identify paths toward enhanced performance, in preparation for upcoming experiments. The NDCX facility accelerates a singly-charged Potassium ion beam to 330 keV at 35 mA with pulse durations 3 µsec to 20 µsec, and then, via an Induction Bunching Module, imparts to a ~100 ns segment of that beam a ±15% head-to-tail velocity ramp, or "tilt." An extended region of neutralizing plasma is generated by a set of ferroelectric plasma sources (FEPS) arranged on the outer wall of the transport line, downstream of the Induction Bunching Module. There, through the process of neutralized drift compression, the selected beam segment bunches longitudinally. Longitudinal compression factors of ~60 have been measured. When the beam is almost fully bunched, it enters a final focusing solenoid (FFS), which further focuses the beam radially. In the vicinity of the target, a set of four cathodic arc plasma sources (CAPS) direct plasma into the beam path; it is primarily this plasma which provides the necessary beam neutralization within the FFS. The parameters of this system (beam energy, Induction Bunching Module voltage waveform, FFS strength, and overall geometry) are adjusted so that the longitudinal and transverse focal planes coincide at the target plane.

For this process to be successful, it is necessary that the plasma density exceed the beam density almost everywhere, so that plasma electrons are free to cancel the strong space-charge field that otherwise would inhibit compression to the desired beam density. Among the main factors limiting the final peak intensity on target is the degree to which gaps in the neutralizing plasma are avoided (other factors include energy fluctuations of the beam, source imperfections, imperfections in the tilt voltage waveform, misalignments, and aberrations in the diode and the magnetic optics). While simultaneous longitudinal and transverse compression in NDCX has enabled our initial studies of targets heated to the Warm Dense Matter (WDM) regime, it is desirable to achieve higher peak intensities so that a broader range of experiments may be fielded. To this end, we have identified two regions of NDCX wherein full neutralization is not in general achieved, and applied both analysis and computer simulations to quantify the effects on the beam. Note that the shaded parts of Fig. 1 are intended to be a schematic representation of the extent of the plasma; they are not the output of a simulation.

The first region with incomplete plasma fill is the "gap" between the FEPS plasma and the plasma in the final focus solenoid. This gap results from the presence, between the neutralized drift compression line with its set of FEPS segments and the FFS, of a gate valve and the associated flanges for connection of the two beamline segments. This gate valve allows either the upstream or (more commonly) the downstream section of the machine to be brought up to atmospheric pressure, independently. There are at least two deleterious effects of this gap: its presence inhibits the flow of plasma into the FFS which would otherwise be driven by the beam's space-charge fields; and (because the electron cyclotron frequency exceeds the electron plasma frequency) it enables a "magnetic compression" effect that leads to a premature and anharmonic collective focusing of the beam. In this effect, the beam ions can cross magnetic field lines (in the fringing field of the solenoid) while the electrons cannot. Due to a concentration of electrons on axis and an incompletely compensated beam-ion charge at larger radii within the beam, beam ions experience a radial electric field. This field has a focusing strength comparable to that of the solenoid and a non-linear variation with position.

The second region with incomplete fill is the "exclusion zone" at larger radii within the solenoid, within which plasma is excluded by the combined effect of the magnetic field geometry, the physical structure of the solenoid and associated mounting hardware, and the placement of plasma sources. In general, it is challenging to inject plasma into a solenoid, because the solenoid's magnetic field acts as a "magnetic mirror" that applies a $\mu\nabla|B|$ force to electrons having magnetic moment μ. Plasma from the CAPS sources begins with a directed velocity that enables the CAPS to fill the solenoid with plasma of density about 10^{13} cm^{-3} near the axis, and out to a radius in the range $2.46\ \mathrm{mm} < R < 4.92\ \mathrm{mm}$ [Roy]. However, the plasma is constrained to flow along the field lines, so at larger radii there is little or no plasma. In NDCX operation the beam radius of up to 1.5 cm in the solenoid implies that many beam ions reside in the plasma exclusion zone. Complicating matters slightly is the fact that persistent eddy currents in the structures holding the solenoid lead to a distortion of the magnetic field away from the shape expected from a simple set of windings; see the right-most field lines in the Figure. These field perturbations do affect the plasma geometry in the FFS and the region between it and the target [Welch].

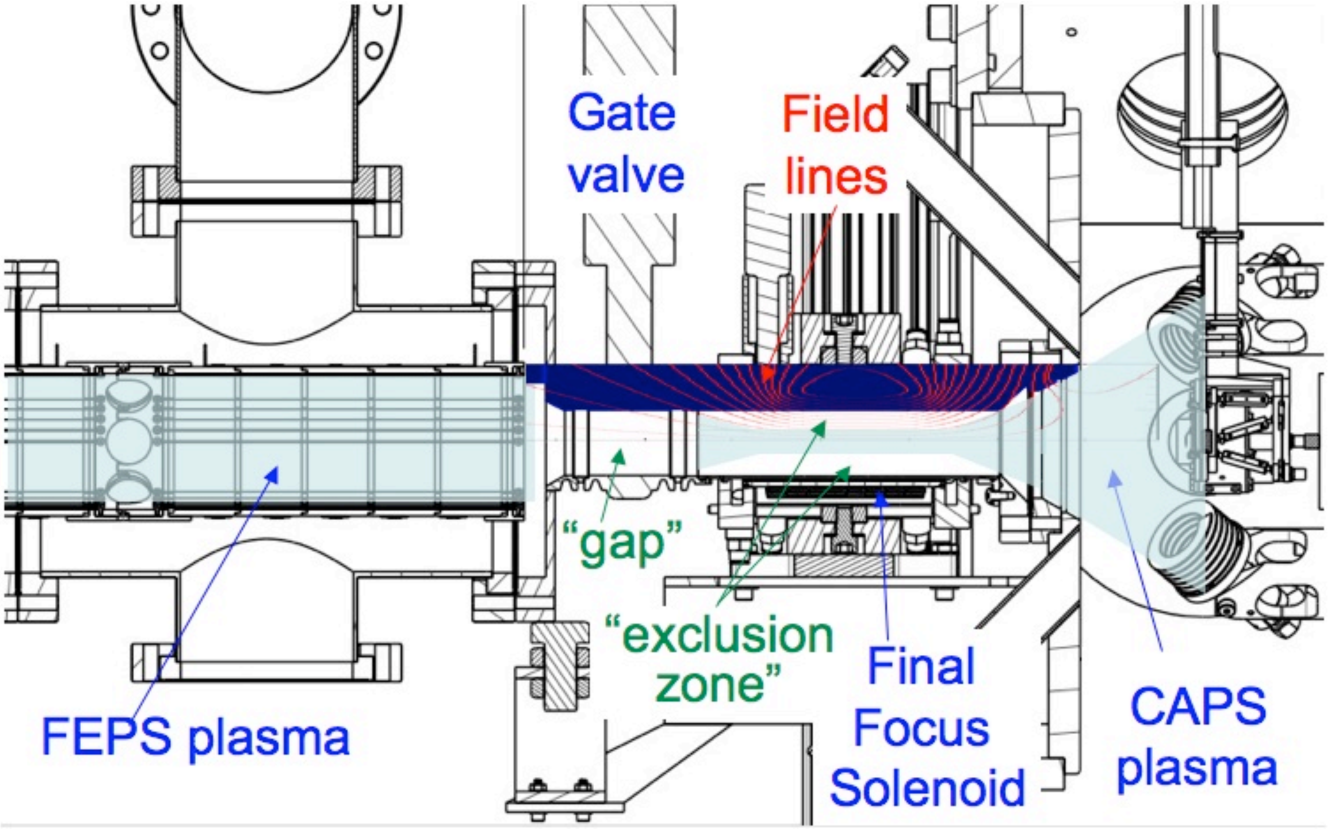

Figure 1. Schematic of downstream end of NDCX, showing regions with incomplete plasma fill: the "gap" between the FEPS plasma and that in the final focus solenoid, and the "exclusion zone" at larger radii within the solenoid. Field lines (red) show eddy current effects (ANSYS calculation).

We have applied both LSP and Warp codes to simulate this system, in order to assess the degradation in the focusing that results from the existence of the gap and/or the exclusion zone. A snapshot (Fig. 2) from one of our Warp simulation runs illustrates the simulation geometry; for results from this run series, see Section III. Many of our runs in this study examined only a sub-domain of the full NDCX system, and/or employed simplifying approximations (such as neglect of internal conductors), in order to achieve numerically converged results with modest computation times. Also, while both codes are capable of 3-D simulations, all of the beam propagation simulation runs presented here use axisymmetric (r,z) geometry.

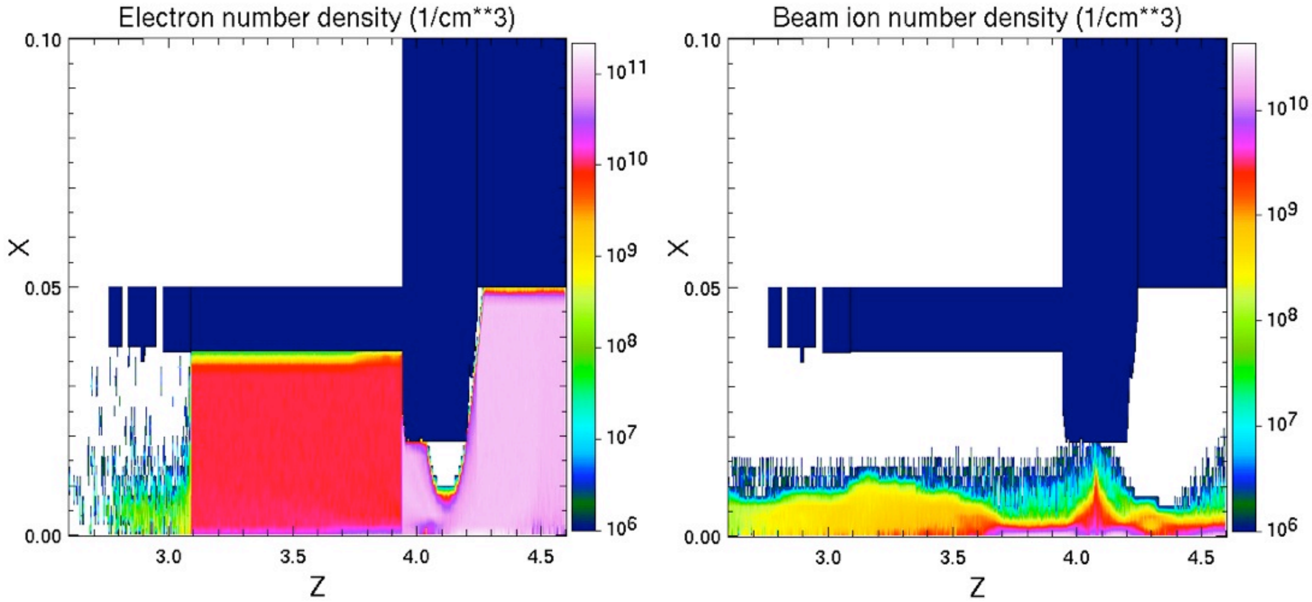

Figure 2. Snapshot from a Warp simulation of NDCX at a time 5.42 μs into the run. On the left, the modeled FEPS plasma (red) and CAPS plasma (magenta) are visible. This run had an "exclusion zone" in the solenoid (with border along a magnetic field line intersecting the edge of the mechanical structure) but no "gap" at the downstream end of the FEPS. On the right, the beam density is denoted by color; the snapshot was taken when the peak in line-charge density fell within the solenoid. Note how the compressed part of the beam extends into the exclusion zone where it cannot be neutralized.

We have also simulated the plasma injection process in 2-D and 3-D. The two codes use different physical models and numerical methods, and so agreement between them validates consistency between the input to and output from the codes that describes the machine geometry, plasma injection, and other physics (such as secondary electron emission from walls). Figures 3 and 4 depict simulations of injection from the CAPS sources using the full kinetic models of LSP and Warp. Other runs have examined FEPS injection (see, *e.g.*, [Welch], [Sefkow], and *the HIFS-VNL's monthly progress report to OFES of 2008-10-31*).

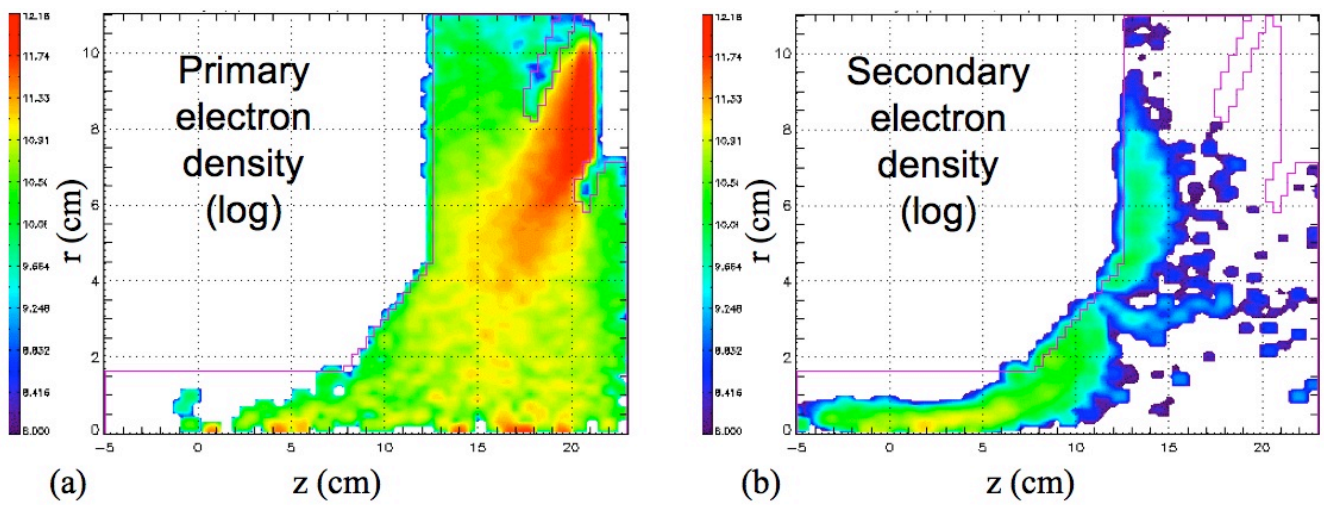

Figure 3. Simulation of plasma injection from CAPS using LSP code. In this case, eddy current effects on the magnetic field distort the field lines (see Fig. 1); secondary electrons are generated at conductor surfaces lying in (0 < r < 6 cm, 6 cm < z < 15 cm); colors denote the logarithm of the electron density.

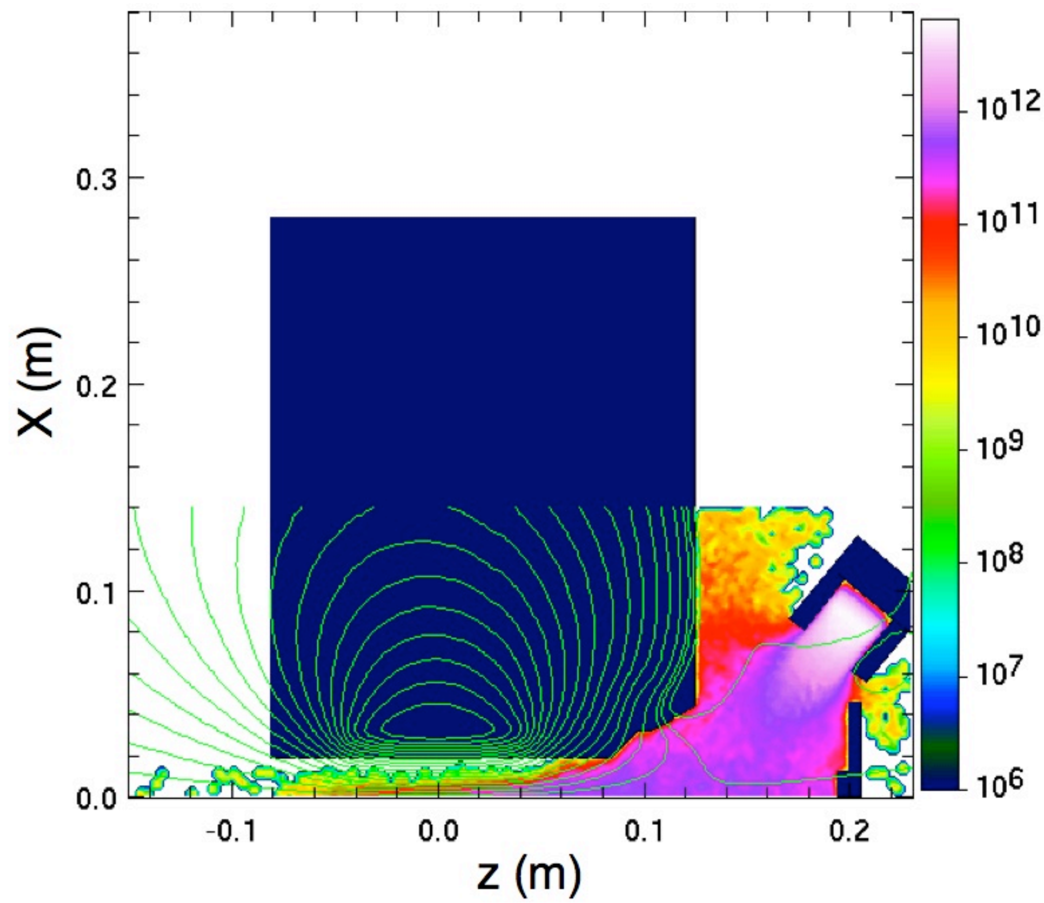

Figure 4. Snapshot at 7.5 μs from 3-D Warp simulation of plasma injection from four CAPS. Colors denote electron number density in cm^{-3} (see scale); note effects of eddy currents on magnetic field.

The remaining sections of this report are organized as follows. In Section II we describe our studies of the influence of collective focusing in the gap between the FEPS and FFS. In Section III we describe or studies of the influence of incomplete plasma filling of the FFS. Finally, in Section IV we describe the implications of this work for the NDCX experiments.

II. Influence of collective focusing in the gap between the FEPS and FFS

Recent experimental and numerical studies have demonstrated a lack of neutralizing plasma in the gap region between the downstream end of the ferroelectric plasma source (FEPS) and the upstream end of the final focus solenoid (FFS) (see Fig. 1). Although moderate beam space charge ($n_b \sim 10^9$-10^{10} cm^{-3}) can be compensated by the plasma electrons dragged by the beam from the FEPS region, collective phenomena occurring in an imperfectly neutralized beam as it traverses the fringe magnetic (B) field at the upstream end of the FFS can significantly influence beam transverse focusing. This field is of the order of several kG, and therefore strong enough that the electron cyclotron frequency is small compared to the plasma frequency: $\omega_{pe} < \omega_{ce}$, where $\omega_{pe} = \sqrt{4\pi n_b e^2 / m_e}$ and $\omega_{ce} = eB/m_e$ are the electron plasma and cyclotron frequencies, respectively. It can be shown that for this case the neutralizing FEPS electrons will follow the magnetic field lines, whereas heavy ions will move almost ballistically across the field lines. As a result, the quasineutrality of the beam breaks down. An excess of beam ion charge develops at intermediate radii, while an excess of negative charge develops in the gap region near the axis of the system, providing a strong radial focusing field, which can affect the beam's final focus (Fig. 5).

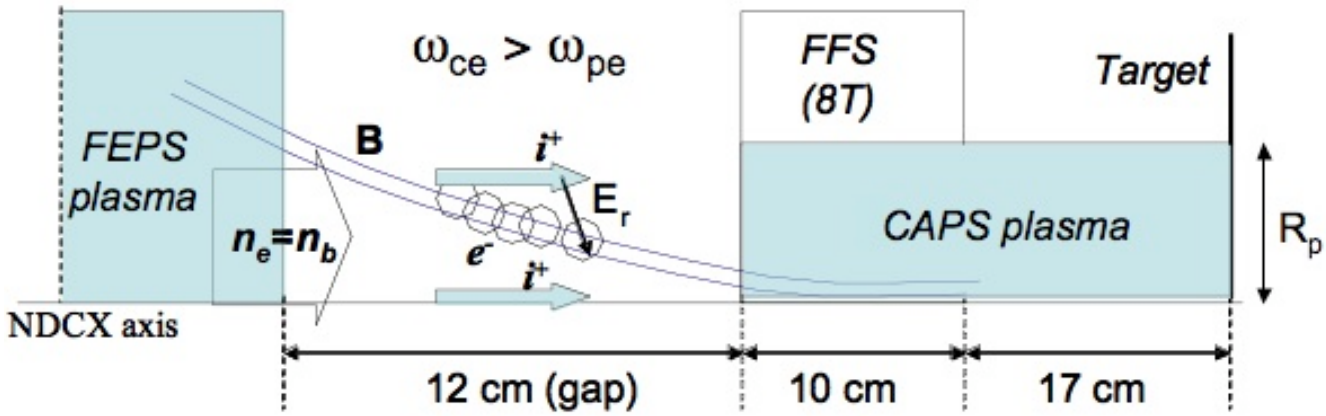

Figure 5. Collective focusing effect in the region between the downstream end of the FEPS and the upstream end of the FFS.

To investigate the collective effects in the gap between FEPS and FFS we have performed idealized numerical simulations. In the simulations the FEPS and CAPS plasmas, with densities of 10^{10} cm^{-3} and 10^{12} cm^{-3} respectively, were treated fully kinetically, allowing for the FEPS- and CAPS-provided electrons to flow into the gap should the forces on them induce such motion. The plasma electron temperature was assumed to be 3 eV. K^+ beam ions with an energy of 320 keV were injected into the simulation through an aperture of r_b=1 cm located inside the FEPS plasma region. To model the effect of the beam prepulse, for the first 40 ns of the total beam pulse the beam current was set to 0.028 A (prepulse), and for the second 40 ns the beam current was set to 0.12 A (compressed portion of the beam). Neither the initial convergence angle nor the longitudinal velocity tilt were included in these runs.

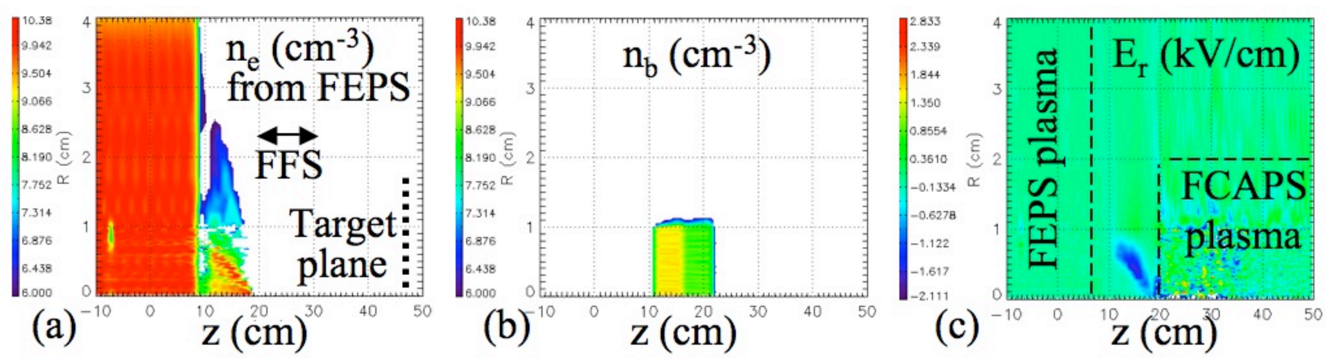

Figure 6. Results of the LSP simulations described in the text at t=230 ns: (a) FEPS electron number density (log scale); (b) beam number density (log scale); (c) radial electric field.

The results of these numerical simulations are shown in Figs. 6-8. Figures 6(a) and (b) show the ion beam and the FEPS electron density; the radial electric field at the same instant is shown in Fig. 6(c). To demonstrate the influence of the radial electric focusing inside the gap we plot the beam density near the downstream end of the FFS [Fig. 7(a)], and compare it to the beam density in the "ideal neutralization" case where the FEPS plasma initially fills the vacuum gap [Fig. 7(b)]. One can see that collective effects in the gap between FEPS and FFS induce premature beam focusing. As the beam propagates from the downstream end of the FFS to the target, a slight decrease in the on-axis beam density is observed. Figure 8(a) shows the beam density at the target plane, and Figure 8(b) corresponds to the "ideal neutralization" case. Note that, due to the anharmonic field of the collective focusing, a large halo tail develops around the focused beam core and the peak beam density is reduced by a factor of about four relative to the "ideal neutralization" case [compare Figs. D (a) and D (b)].

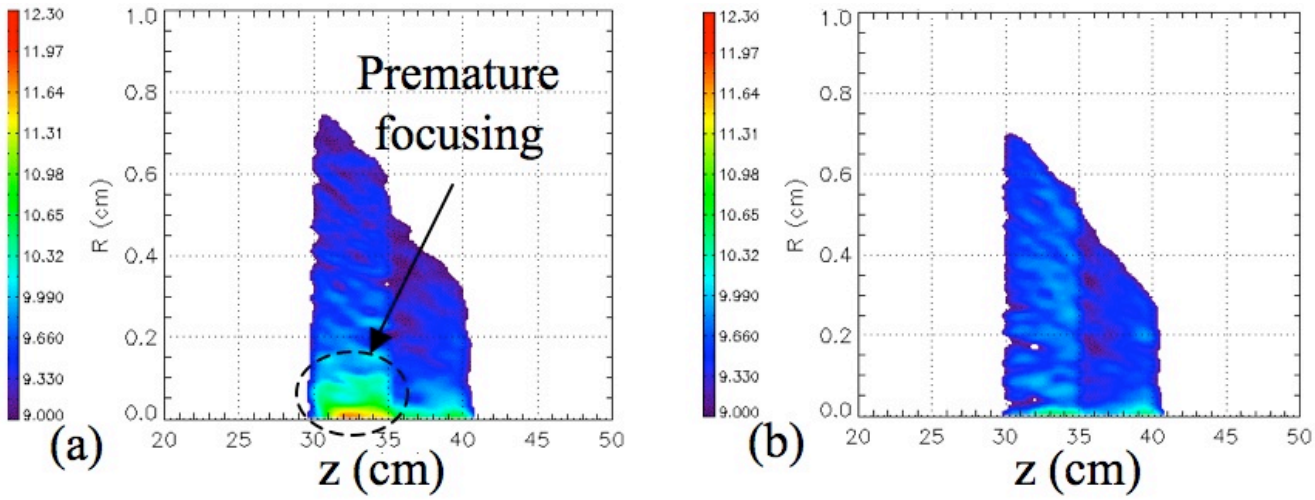

Figure 7. Ion beam density (log scale) at downstream end of the final focus solenoid (FFS). (a) The gap distance between FEPS and FFS is 12 cm; (b) Ideal neutralization case (the FEPS plasma fills the gap).

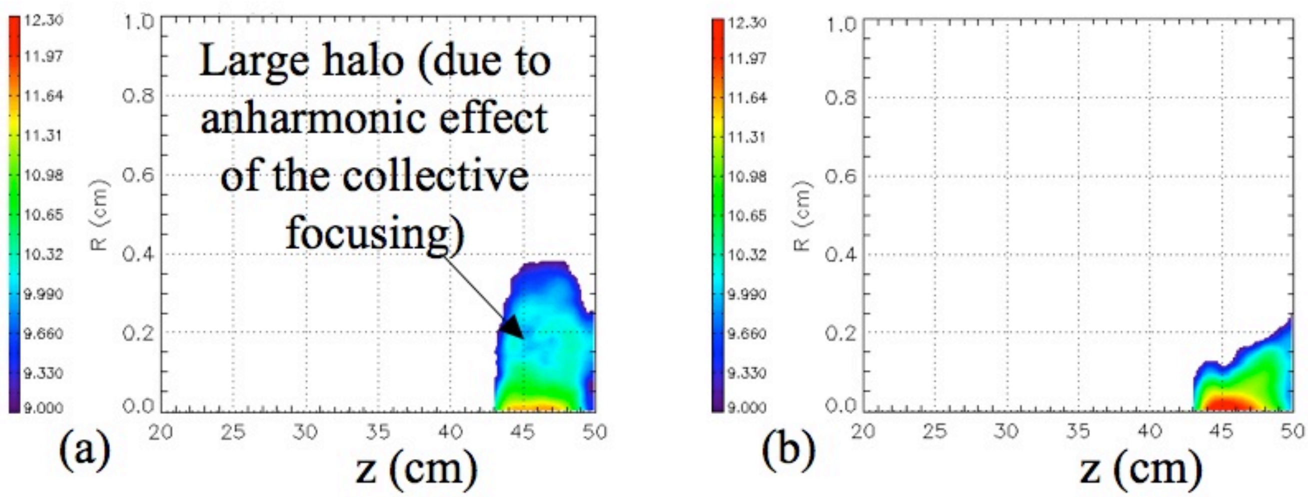

Figure 8. Ion beam density (log scale) at the target region. (a) The gap distance between FEPS and FFS is 12 cm; (b) Ideal neutralization case (the FEPS plasma fills the gap).

This collective focusing effect was studied for different values of the beam density. It was found that the radial electric field is greater for higher beam densities. Therefore, the degrading influence of these collective effects is less pronounced for the beam prepulse than for the compressed portion of the beam. This is consistent with the experimental observations demonstrating better transverse focusing of the beam prepulse. In other studies we found that the collective focusing effect persists even for longer beam pulses, long enough (410 ns) that the beam itself provides a conducting path across the gap.

The two codes yield similar results. With Warp we are using an electrostatic model for these studies, and so are able to display the electrostatic potential. In Figure 7 we show snapshots from one such run. At 240 ns, the beam extends from 12.5 cm to 23 cm, with the main pulse extending from 12.5 cm to 18 cm. At 264 ns, the beam extends from 15.5 cm to 26 cm, with the main pulse extending from 15.5 to 21 cm. CAPS plasma fills the region near the solenoid axis ($z > 0.2$ m, $r < 5$ mm). Note the regions of positive potential in blue-cyan due to excess positive (beam ion) charge, and of negative potential in orange-yellow due to excess electron charge. The electrons have adjusted their positions by moving along field lines but cannot completely overlay the beam ions. The strong field associated with the collective focusing arises as the gradient of the potential difference, and is centered at about $z = 0.15$ m; for comparison, the results of the LSP run shown in Fig. 6(c) show the radial electric field itself.

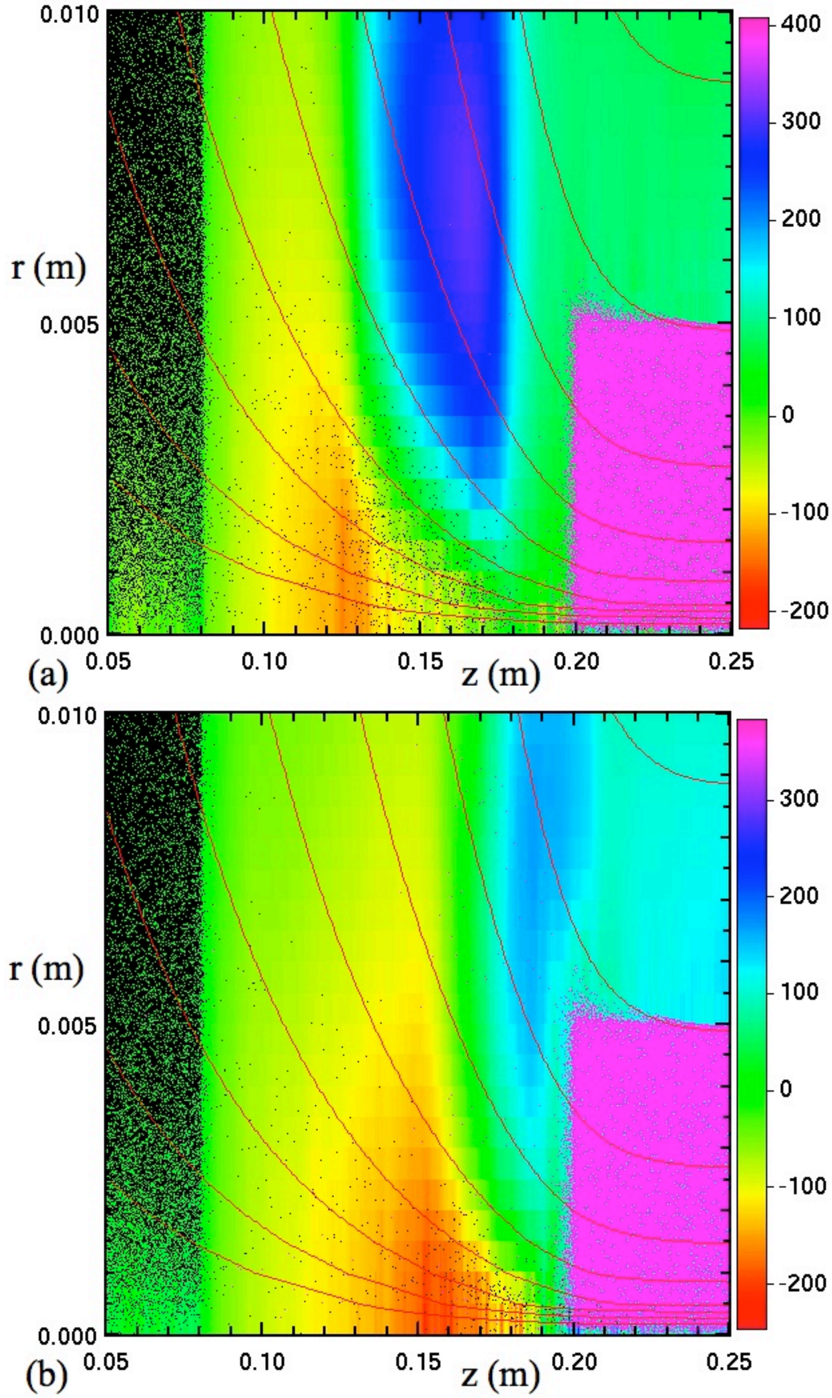

Figure 7. Snapshots from a Warp simulation of beam passage through the "gap" (plasma void) region in NDCX, at (a) 240 ns, and (b) 264 ns. The full simulation domain was (-7 cm < z < 55 cm, 0 < r < 4 cm), the FEPS density was $2x10^{10}$, and the CAPS density was 10^{12}. Black dots denote FEPS electrons; magenta dots denote CAPS electrons (these simulation particles each carry a ten-times higher "weight" than the FEPS electrons, since the CAPS plasma is denser); lines are magnetic field lines; and colors denote the electrostatic potential (Volts) as indicated on the scale at right.

From our simulations we have learned that some of the electrons from the FEPS plasma are pulled into the gap between that region and the FFS as the beam passes into and through that gap. In addition, when the beam enters the gap, some of the electrons from the CAPS plasma in the FFS are attracted to the bare beam charge, and flow upstream to partially neutralize that charge. To better understand these processes, and to further clarify the nature of the collective focusing effect, we carried out simulations with both codes that employed higher spatial resolutions, with grids fine enough to resolve the electron Debye length (this was made easier by using altered parameters). We also carried out idealized Warp runs modeling electron flow from a reservoir into a gap containing an ion-filled region. The incomplete neutralization appears to be due to the absence of a strong damping mechanism for the electron motion (two-stream instability is insufficient because the evolving space charge field leads to a broad thermal distribution of electrons).

Figure 8 shows snapshots at a time when the beam completely fills the gap, from an LSP simulation wherein the Debye length was resolved. The CAPS plasma density was 2×10^{10} cm^{-3}, the FEPS plasma density was 2×10^{11} cm^{-3}, the beam density was 2×10^{9} cm^{-3}, the electron temperature 10 eV, and the Debye length 0.0052 cm. Variable grid spacing in z was employed, but sheath regions were well resolved. As can be seen, the electrons from the CAPS plasma in the solenoid are free to enter the gap along the magnetic field, and to overlay the full radius of the beam; however, they overshoot the beam and fill a larger volume more tenuously. The CAPS electron phase space shows how electrons come off the CAPS plasma with negative velocity, but are turned around by the beam charge and acquire positive velocity, and indeed set up a circulating flow. Note that the region in Fig. 8(a) immediately above z = 0 is special, since it is where the beam is generated in this run; also, the CAPS electron phase space in the FEPS region (z < 10 cm) may display associated artifacts.

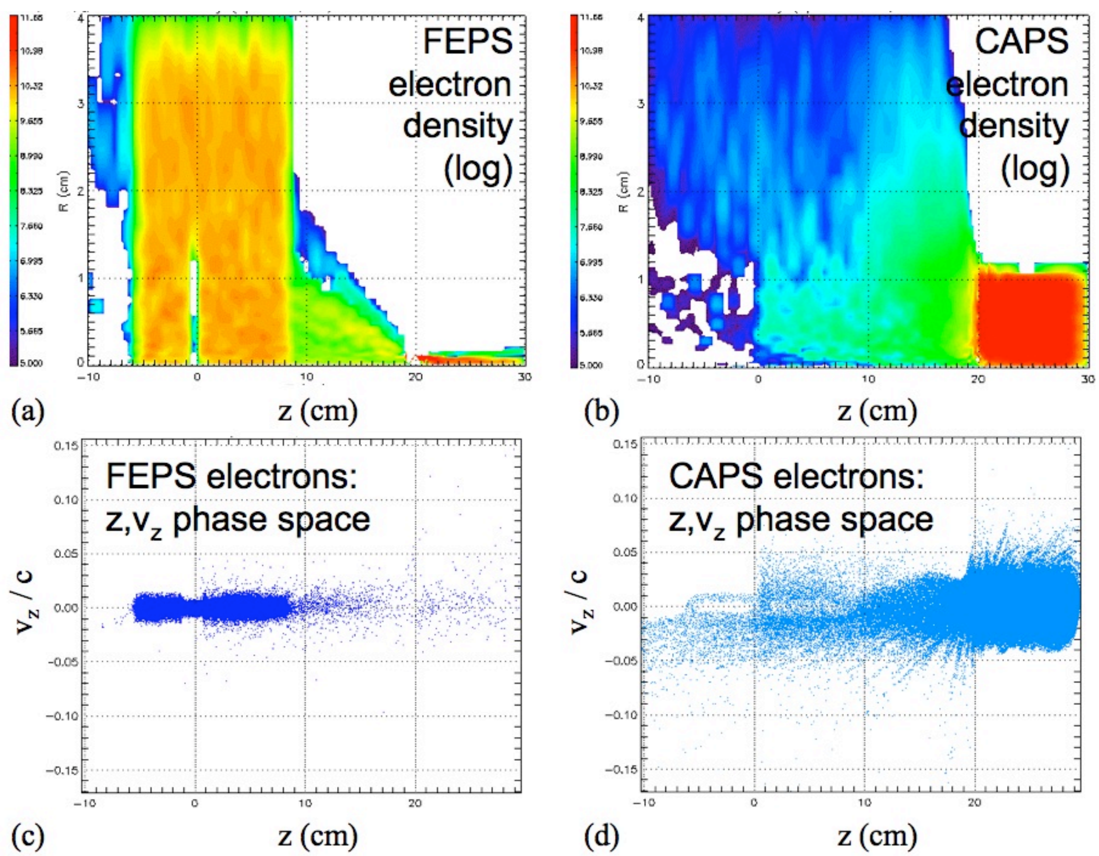

Figure 8. Snapshots from a well-resolved LSP simulation of the gap region, showing (a) FEPS electron density; (b) CAPS electron density; (c) FEPS electron phase space; and (d) CAPS electron phase space.

III. Influence of incomplete plasma filling of final focus solenoid

We have carried out integrated Warp simulations of beam propagation through NDCX, beginning from the beam source, and using specified initial plasma distributions. For an example, see Fig. 2 (which assumed $r_p = 7.4$ mm). The plasma in each run filled the final-focusing solenoid (FFS) out to a magnetic flux surface (level surface of rA_θ) with minimum radius specified in the run input file. There was no gap between the ferro-electric plasma source (FEPS) and the plasma in the FFS that was generated by the cathodic arc plasma sources (CAPS). The beam energy fluence at the target plane is relatively insensitive to this plasma radius when it is sufficiently large (4.5 mm or greater); see Fig. 9. The peak value in these nearly-ideal simulations is 150-200 mJ/cm^2. However, the plasma at the midplane of the FFS as diagnosed has a radius between 2.46 mm and 4.92 mm. For a plasma radius of 2.5 mm, the simulated fluence is 70 mJ/cm^2. Note that the runs reported in [Welch] used a higher initial ion beam energy and current at the source, along with somewhat differencing focusing, and yield higher ideal-case fluences. NDCX experiments for similar conditions have obtained a peak energy fluence in the compressed beam of 15 mJ/cm^2. The plasma-poor gap upstream of the FFS, not included in these runs, contributes to additional degradation; other effects, such as a non-uniform plasma from the CAPS, and/or a misaligned beam which is off-axis in the FFS, may also be at play.

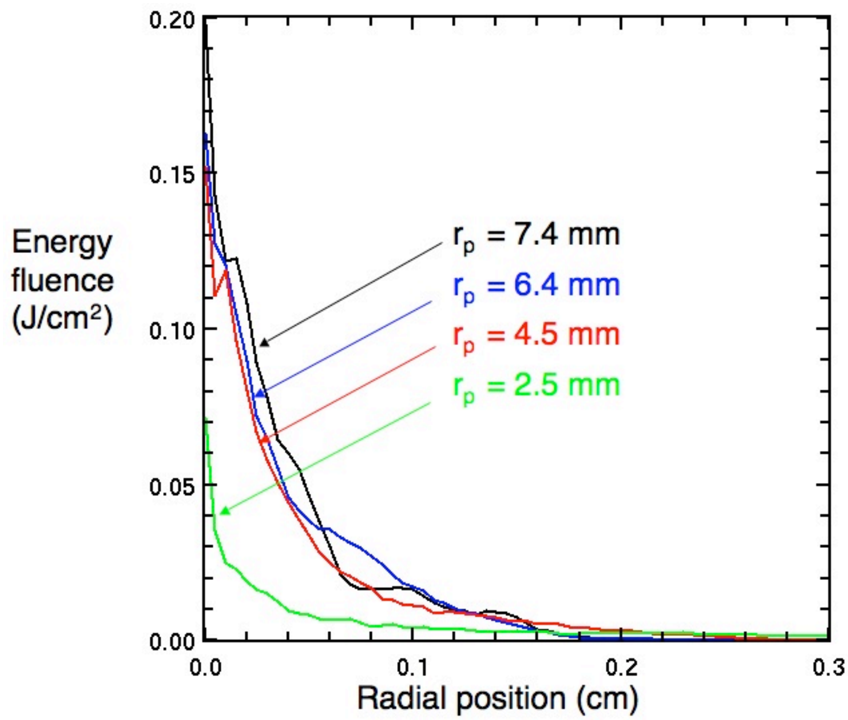

Figure 9. Energy fluence on target plane (time integral of beam power over a 10 ns window centered at the time of peak power) versus radial position, for various assumed CAPS plasma fill radii as indicated, for integrated Warp simulations.

We have also carried out Warp simulations using a more idealized model (as discussed above in connection with Fig. 7) with a 35 mA beam, modeling the uncompressed part of the pulse only, and not the ~2 A compressed peak. Various combinations of gap length and plasma radius within the FFS were employed. Snapshots of the electron number density in two such runs are shown in Fig. 10.

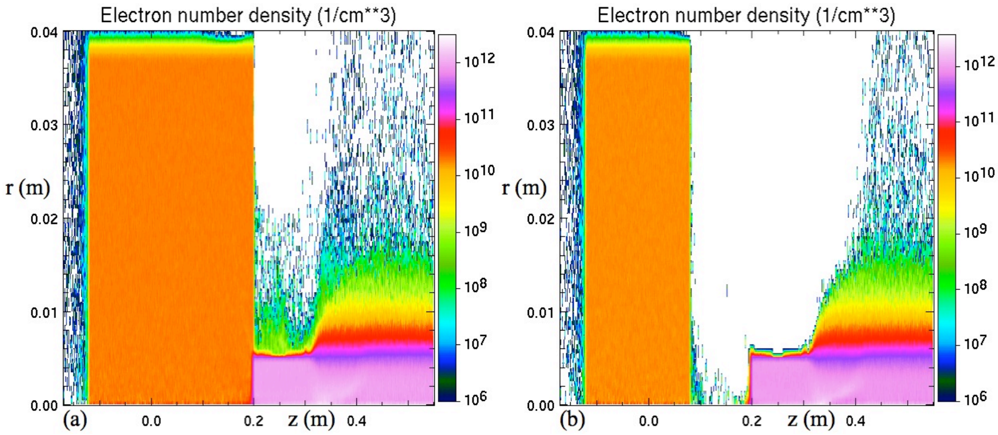

Figure 10. Snapshots of electron density in idealized Warp simulations with: (a) no gap; (b) 12 cm gap; the beam center is at about 0.25 m, and electrons are pulled along with the beam in the former case. Note that no internal conducting boundaries were used; thus FEPS plasma could flow into the FFS, while in reality it would be blocked.

The results of these idealized Warp runs are summarized in Fig. 11. Note that this plot covers a narrow radial range near the axis, out to only 0.5 mm. Also, the fluences shown are averages over very small radial zones; the experimental measurements use a coarser measure. They were computed for uncompressed pulses using a long (40 ns) window. For the most part, the deleterious effects of gap and limited plasma radius are roughly additive. Collective focusing is stronger for a compressed pulse, so these results underestimate its impact on a bunched beam.

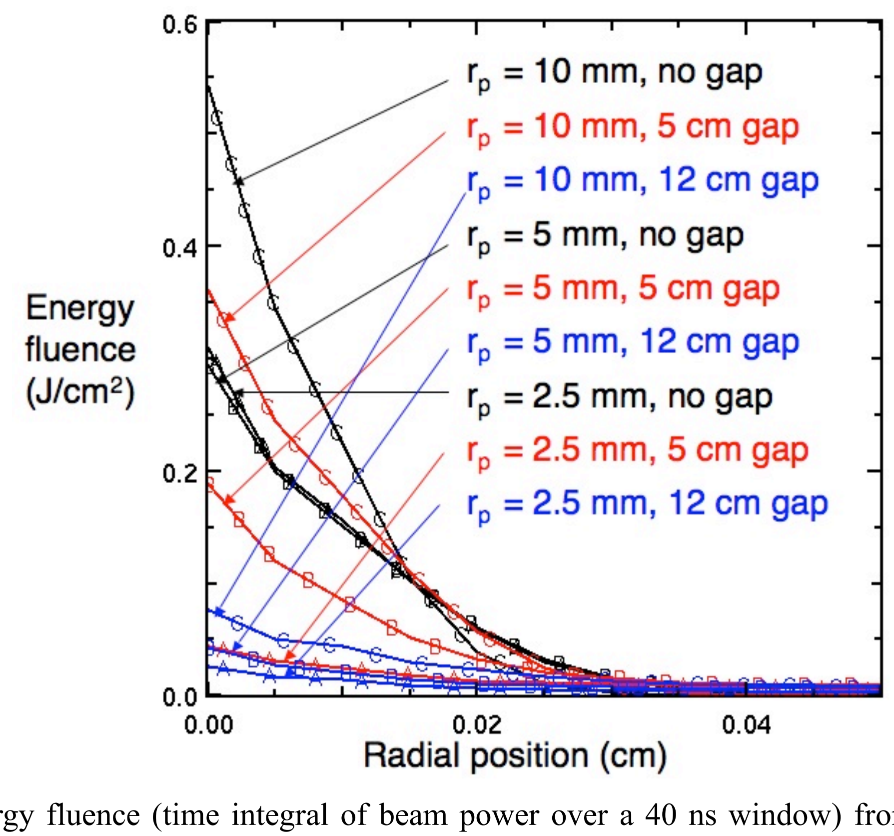

Figure 11. Energy fluence (time integral of beam power over a 40 ns window) from idealized Warp simulations of unbunched beam, showing effects of gap and limited radius plasma. Black curves correspond to runs with no gap, red a 5 cm gap, blue a 12 cm gap. Curves labeled A correspond to runs with a 2.5 mm radius CAPS plasma, B a 5 mm plasma, and C a 10 mm plasma.

IV. Implications for NDCX experiments

We have begun to examine what is required to minimize the gap region between the ferro-electric plasma source (FEPS) and the final-focusing solenoid (FFS). Due consideration must be given to the role of the gate valve, which facilitates efficient machine operation. It appears feasible to interchange the final section of the FEPS with the gate valve; suitable provision for electrical feed-through to the repositioned FEPS section would have to be made, but this should be possible. In the existing machine configuration, flanges would still be needed to attach that FEPS section to the FFS, and so we might expect that the plasma-free gap might be reduced to about 5 cm without major machine redesign. We believe that even such an incomplete elimination of the gap would improve machine performance.

With regard to introducing plasma into the “exclusion zone” at large radius in the solenoid, we are considering introduction of compact plasma sources on the plasma wall, near the end of the solenoid. Preliminary considerations of the feasibility of this are encouraging. Such sources would directly insert plasma where currently there is none, and allow the full-radius compressed beam to be fully neutralized while in the FFS. Specifically, we consider new miniature CAPS that could produce streaming metal plasma at strategic locations where the magnetic field lines intersect the solenoid-enclosing body. Such CAPS could be simple, custom-made miniature sources which are essentially a coaxial structure with the central metal being the “feedstock” for the plasma. The outer “shield” of each structure would provide the current return path. The power supplies could be modeled after the pulse-forming network supplies currently used for the existing larger CAPS.

More “exotic” configurations are possible, and may be desirable. One concept involves placement of a second solenoid behind the target plane, with opposite polarity but weaker strength than the FFS, so as to make a spindle-cusp field. The unequal strength allows the cusp field to be angled so that plasma from the sources flows ballistically toward the FFS. An advantage is that sources could be arranged at large radius, at a larger number of positions around the system wall; the plasma would converge radially onto the axis, yielding a higher density plasma. A very preliminary simulation of a symmetrical cusp arrangement was encouraging. Such a major change would require much further study.

On the basis of these studies, we believe that the performance of NDCX, as measured by the peak energy fluence on the target, would be enhanced by introducing additional neutralizing plasma in key regions. In particular, these simulations suggest shortening the gap region between the ferro-electric plasma source (FEPS) and the final-focusing solenoid (FFS), introducing plasma into the FFS at larger radius by means of additional sources, or ideally doing both of these things.

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